

Microwave photoresponse in the 2D electron system caused by intra-Landau level transitions

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(February 2, 2008)

The influence of microwave radiation on the DC-magnetoresistance of 2D-electrons is studied in the regime beyond the recently discovered zero resistance states when the cyclotron frequency exceeds the radiation frequency. Radiation below 30 GHz causes a strong suppression of the resistance over a wide magnetic field range, whereas higher frequencies produce a non-monotonic behavior in the damping of the Shubnikov-de Haas oscillations. These observations are explained by the creation of a non-equilibrium electron distribution function by microwave induced intra-Landau level transitions.

The strong recent interest in the microwave photoresponse of high-quality two-dimensional electron systems has been triggered by the discovery [1,2] (also [3–7]) of zero-resistance states in the vicinity of the cyclotron resonance harmonics. These states developed out of the minima of earlier reported microwave induced magnetoresistance oscillations [8,9]. Theories capable of accounting for these oscillations are based on several different approaches. They include (i) indirect inter-Landau-level transitions, which involve the absorption of a microwave quantum and are accompanied by scattering processes that alter the electron momentum [10–17], (more general considerations in terms of the quantum Boltzmann equation were given in Ref. [18]), (ii) the establishment of a non-equilibrium electron energy distribution function including inverted occupation of the electronic states under appropriate conditions [3,19,20], (iii) photon assisted quantum tunnelling [21], and (iv) nonparabolicity effects [22]. Most of the cited articles treat the magnetoresistance of a homogeneous state and conclude that it may become negative. Additional theoretical activity concentrated on explaining the appearance of zero-resistance in experiment instead. It is argued that negative values of the dissipative conductivity lead to instabilities [23]. As a result, an inhomogeneous domain structure, which produces zero resistance, may form [18,21,24–27].

Up to now considerations were limited mainly to the weak magnetic field range where the microwave frequency ω exceeds the cyclotron frequency ω_c and inter-Landau level transitions are of great importance. Here, we are concerned with the influence of the microwave radiation on the magnetoresistance and the amplitude of the Shubnikov-de Haas (SdH) oscillations in the opposite regime when $\omega < \omega_c$. Inter-Landau-level transitions then no longer play a role. At comparatively low-frequency radiation, we experimentally observe a strong suppression of the magnetoresistance accompanied by a drop in the amplitude of the SdH oscillations [28]. At higher radi-

ation frequencies, the SdH oscillations are also strongly damped except for a narrow region of the magnetic field B , where the amplitude is rather insensitive to the radiation. We attribute the magnetoresistance and the SdH oscillation suppression to the non-equilibrium electron occupation caused by microwave induced intra-Landau level transitions. The unusual non-monotonic damping of the SdH-oscillations at higher frequencies reflects the crossover from the inter- to intra-Landau-level transition regime in the case of non-overlapping levels.

We have measured 3 Hall bar samples produced from two different wafers of the standard architecture containing a two-dimensional electron system at a single remotely doped GaAs/AlGaAs heterojunction with a spacer width of 80 nm. The mobility after illumination reached values between $6 - 15 \times 10^6 \text{ cm}^2/\text{Vs}$ at a typical saturated density of $3 \times 10^{11} \text{ cm}^{-2}$. The channel widths of the samples were equal to 0.05, 0.2 and 0.4 mm. All samples demonstrated qualitatively the same results. The main difference was the amplitude of the microwave induced oscillations. The samples were mounted in a waveguide with a cross-section of $16 \times 8 \text{ mm}^2$ (WR28) and submerged in pumped ^3He . The ρ_{xx} and ρ_{xy} magnetoresistivity tensor components were measured with lock-in technique using a 10 Hz sinusoidal current.

Typical experimental curves are shown in Fig. 1. In the absence of microwave radiation, ρ_{xx} exhibits the usual SdH oscillations. Radiation with frequency ω dampens these oscillations at low B -fields and gives rise to the microwave induced magnetoresistance oscillations (see also Fig. 2) with minima located where $\omega \approx \omega_c(k + 1/4)$ (Here $k = 1, 2, \dots$). As seen in Fig. 1 low frequency radiation (for our samples less than 40 GHz) also dramatically suppresses the average magnetoresistivity within a wide B -field range and even when $\omega_c \gg \omega$. For the particular case of Fig. 1, the magnetoresistivity ρ_{xx} at for instance 0.2 T ($\omega_c/\omega \approx 5$) is reduced by one order of magnitude and becomes less than the zero-field resistivity by about

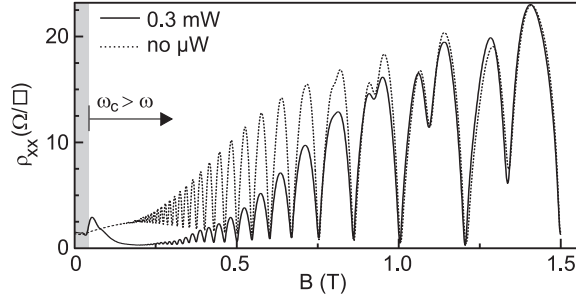


FIG. 1. Magnetoresistivity ρ_{xx} versus B in the absence of radiation (dotted line) and under 17 GHz radiation (solid line) at $T=0.4$ K and density $n_s = 2.92 \times 10^{11} \text{ cm}^{-2}$. The microwave power $P = 0.3 \text{ mW}$ was measured at the oscillator output. The microwave electric field is perpendicular to the current.

a factor of 5. In the single-mode regime of the waveguide, i.e. for frequencies below 19 GHz, this drop in ρ_{xx} was observed for both orientations (parallel and perpendicular) of the microwave electric field with respect to the excitation current. Fig. 2 depicts how this ρ_{xx} suppression evolves with microwave frequency [29]. It reduces at higher frequencies and disappears near 40-50 GHz. At these higher frequencies, plotting the magnitude of each SdH oscillation, $A(P)$, normalized to its amplitude in the absence of microwave radiation, $A(0)$, reveals a non-monotonic behavior as a function of B as seen for instance in Fig. 3b. Note that data presented in Fig. 3 have been measured at more than one order of magnitude smaller power than data depicted in Fig. 2. Fig. 3a shows such low power data for 40 GHz. Maxima of $A(P)/A(0)$ in Fig. 3b, nearly symmetrically arranged around $B = 0$, are located in the vicinity of the second cyclotron resonance subharmonic, i.e. when $\omega = \omega_c/2$. The asymmetry of the curves (especially at lower frequency) with respect to $B = 0$ is tentatively assigned to the excitation of edge magnetoplasmons by the radiation in view of their chiral properties [30]. At the maxima, $A(P)/A(0) \approx 1$, i.e. the SdH oscillation amplitude is insensitive to the applied low power microwave radiation. The red shaded box in Fig. 3a highlights this region for the 40 GHz data.

To account for these observations, we first address qualitatively what microwave absorption processes can take place when considering energy conservation, while assuming other selection rules are relaxed due to the inevitable disorder in the samples. In Fig. 4, the regions in the (ω_c, ω) -plane where inter- and intra-Landau level transitions can occur are color coded. These areas are bounded by two lines: $\omega = \omega_c - 2\Gamma/\hbar$ and $\omega = 2\Gamma/\hbar$. Here, Γ is half the width of a broadened Landau level. When the cyclotron radius r_c exceeds the characteristic length scale, λ , of the random potential, this width increases with the square root of the applied B [31,32]. The border lines for inter- and intra-Landau level transitions then intersect when $\omega_c = \omega_{c0}$ and $\omega = \omega_0 = \omega_{c0}/2$, i.e.

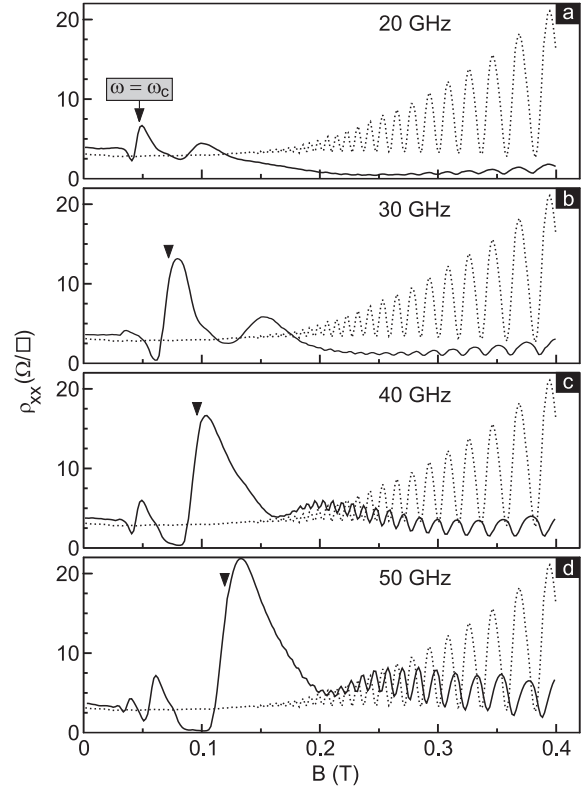


FIG. 2. Magnetoresistivity ρ_{xx} versus B without radiation (dotted lines) and under microwave radiation (solid lines) for the marked frequencies at $T=0.4$ K and $n_s = 2.8 \times 10^{11} \text{ cm}^{-2}$. The oscillator output power P was equal to 2 mW. The positions of the cyclotron resonance are marked by arrows.

when the microwave frequency coincides with the second subharmonic of the cyclotron resonance frequency ω_{c0} . For $\omega < \omega_0$, there are always transitions possible. They may modify the electron distribution function, which affects the conductivity (resistivity) and the SdH oscillation amplitude [3,19,20] and produces the dramatic drop in ρ_{xx} as shown later. However when scanning the B -field at a fixed microwave frequency slightly exceeding ω_0 , the white region where we anticipate very weak absorption is briefly entered. It is likely responsible for the maxima in the 40 and 50 GHz curves of Fig. 3b where the amplitude of the SdH oscillations is only weakly influenced by the radiation. A similar non-monotonic behavior of the SdH oscillation amplitudes is expected from Fig. 4 at $\omega_c = \omega_{c0}$ and $\omega = 3\omega_0$. This was indeed confirmed in experiment. For $f = 121$ GHz in Fig. 3c near $B \approx 0.18$ T, the SdH oscillations are insensitive to radiation. Surprisingly, such straightforward considerations explain quantitatively the experimentally observed position of the maxima. It is worth noting that, within this picture, the decay of $A(P)/A(0)$ beyond the maxima in Fig. 3b at higher absolute values of B implies that the Landau level width increases with B . Then, for frequen-

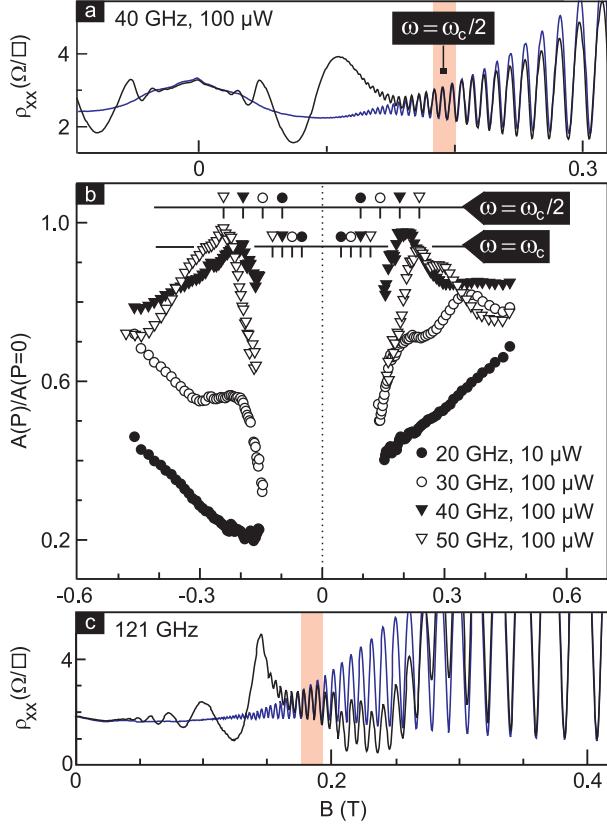


FIG. 3. (a) ρ_{xx} versus B without (blue) and with 100 μW of 40 GHz radiation. (b) The amplitude of each SdH-oscillation under microwave radiation with power P , $A(P)$, normalized to its dark value, $A(P=0)$, is plotted for different microwave frequencies. The location of the cyclotron resonances and second cyclotron resonance subharmonics are marked. (c) ρ_{xx} vs. B without (blue) and with 121 GHz radiation. The red shaded box, where $\omega \approx 3\omega_c/2$, demarcates as in (a) the region where SdH oscillations do not respond to microwaves.

cies exceeding ω_0 the low field region with predominant inter-Landau level transitions is followed by no transitions and finally by a field regime where intra-Landau level transitions occur. This field dependent broadening is distinctive of a short-range random potential for which $\lambda \leq r_c$ [31,32]. In remotely doped heterojunctions, the shortest range of the random potential is frequently given by the spacer width. In our samples the cyclotron radius becomes smaller than the spacer width at $B > 1$ T. The presence of fluctuations on a length scale $\lambda < r_c$ at low fields allows intra-level transitions.

To substantiate the assertion that the strong reduction of the average magnetoresistance for $\omega \ll \omega_c$ can be attributed to changes in the electron distribution function, we have analyzed whether the recently proposed theory in Ref. [20] is capable of reproducing this phenomenon. As initially suggested in Ref. [3], this theory considers the nonequilibrium population of electronic states. In

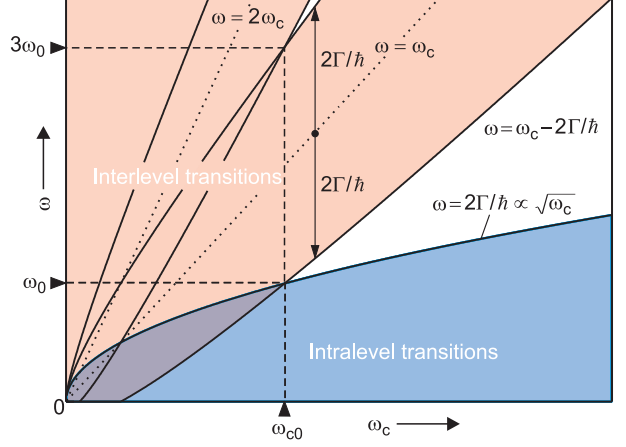


FIG. 4. The (ω_c, ω) -plane. Regions where inter- and intra-Landau level transitions can occur under microwave radiation are color coded. The main boundaries are formed by $\omega = \omega_c - 2\Gamma/\hbar$ and $\omega = 2\Gamma/\hbar$. They intersect at $\omega = \omega_0 = \omega_{c0}/2$. In the white regions energy conservation prohibits transitions. The position of the cyclotron resonance and its second harmonic (straight dotted lines) are also shown.

addition, it allows for finite temperature and inelastic relaxation. We have solved numerically the equation for the non-equilibrium distribution function of Ref. [20] (Eq. (2)) for the case of non-overlapping Landau levels, while omitting the term describing effects caused by the dc electric field. We further assume that spin splitting is not resolved. Calculated traces of ρ_{xx} for frequencies $\omega_1 < \omega_0$ and $\omega_2 > \omega_0$ are shown in Fig. 5. A damping of the SdH oscillations at intermediate values of ω_c/ω accompanied by a strong suppression of the average magnetoresistivity is apparent in Fig. 5a for $\omega_1 < \omega_0$, qualitatively confirming observations in Fig. 1 and 2. The magnetoresistance suppression is a result of the strong modification of the distribution function mainly within the highest occupied Landau level caused by intralevel transitions as evident from the right inset. Even in the presence of inelastic relaxation, energy ranges with inverted electron populations exist, which yield a negative contribution to the magnetoresistance not unlike what occurs at $\omega > \omega_c$ where the zero resistance states develop. Fig. 5b for $\omega_2 > \omega_0$ demonstrates the insensitivity of the SdH oscillations located around the second cyclotron resonance subharmonic (i.e. when $\omega = \omega_c/2$) to the microwave power in a narrow magnetic field region, highlighted in red. This is consistent with the data in Fig. 3.

From the appearance of the maxima in $A(P)/A(0)$ at 40 GHz and their location in Fig. 3b, the Landau level width can be estimated. The data suggest $2\Gamma/\hbar\omega_c = 0.5$ when $B \approx 0.18$ T. This estimate seems to be in reasonable agreement with the lower magnetic field limit where we are able to resolve the SdH oscillations (0.1 T at $T=0.4$ K).

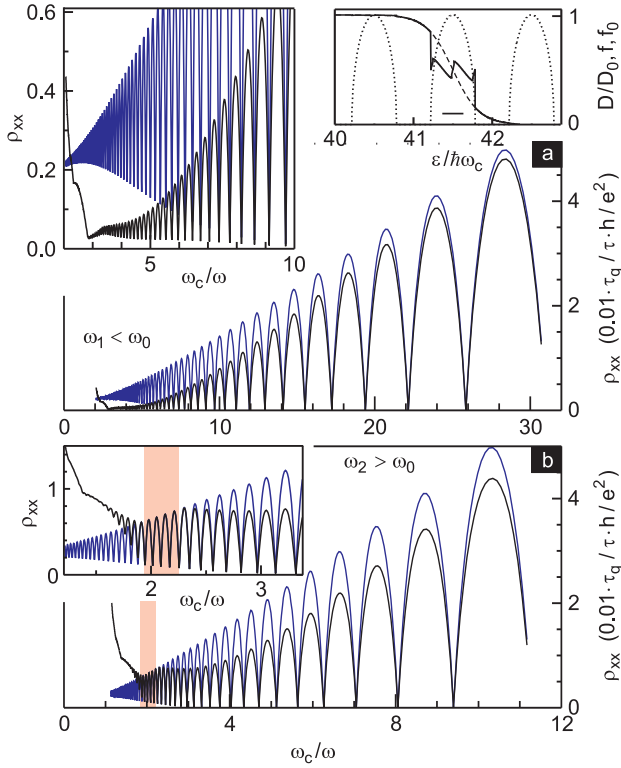


FIG. 5. Calculation of ρ_{xx} vs. ω_c/ω (or B) (black solid lines) for frequencies $\hbar\omega_1 \approx 0.42\hbar\omega_0 \approx 6.5 \times 10^{-3}\epsilon_F$ (a) and $\hbar\omega_2 = 1.15\hbar\omega_0 \approx 0.018\epsilon_F$ (b) and for the dimensionless microwave powers $P_\omega^{(0)}$ [20] (proportional to ω^{-4}) of 100 and 10 respectively. The temperature $T \approx 4.0 \times 10^{-3}\epsilon_F$. Here ϵ_F is the Fermi energy at zero B -field. Blue lines present the calculated magnetoresistivity in the absence of radiation. The left insets are expanded views (same units as main panels). The right inset in the top panel depicts the semi-elliptical density of states D/D_0 (dotted line) [31] and calculated distribution function $f(\epsilon)$ (solid line) under microwave radiation for the point $\omega_c/\omega \approx 3.7$, corresponding to filling factor 83. Here, $f_0(\epsilon)$ (dashed line) is the Fermi distribution function, with $D_0 = 2/\pi^2 l_B^2 \Gamma$ and l_B the magnetic length. The value ω_1/ω_c for the chosen magnetic field is plotted in the inset as a line segment. In the bottom panel, the magnetic field interval where the SdH oscillations are not affected by radiation is demarcated by the red shaded box.

In summary, we have presented experimental data showing a dramatic suppression of the magnetoresistance across a wide field range where microwaves can, under the condition of single photon absorption, only induce intra-Landau level transitions. The regime where intra-Landau-level transitions start to take over from inter-Landau level transitions is detected from the anomalous damping behavior of the SdH oscillations. This anomaly allows to estimate the Landau level width.

The authors gratefully acknowledge fruitful discussions of the manuscript with A. Mirlin, D. Polyakov, and I. Dmitriev and financial support by INTAS, RFBR

(SID), the GIF and the DFG.

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